# Finite Element Modeling of Five Phase Permanent Magnet BLDC Motor for High Power Density Application

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Article Info	ABSTRACT
Article history: Received Jun 18, 2013 Revised Oct 12, 2013 Accepted Oct 23, 2013	Fault-tolerant capability of electrical motor drives is an essential feature in applications such as automotive, aeronautic, and many others. A multi-phase permanent-magnet BLDC motor exhibits a high fault tolerant capability hence increasing the reliability, as it can be designed to reduce the fault occurrence as well as to operate indefinitely in the presence of fault, keeping the mininimum requirements. With multi independent phases, in the event of
<i>Keyword:</i> Brushless motors Fault-tolerant system Finite elements analysis Multiphase	failure of one or more, the remaining healthy phases let the motor to operat properly. This paper presents finite element modeling and results of a five phase permanent magnet brushless motor designed for high power densit application, exploring the characteristics of multiphase topology.
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### 1. INTRODUCTION

Permanent magnet BLDC motors exhibit well-known attractive features such as high efficiency, good operating performance, and better torque-to-current ratio last feature being particularly suited when the motor must be overrated to sustain the lack of one or more phases, whereas the stator winding short circuit current (fed by the rotor magnet back-EMF) can be limited by a proper design of the leakage inductance. The use of more than three phases makes possible to obtain high torque reserve both to allow increased dynamic performance of the machine and to extent operation in the case of damage in some phases by simply disabling the faulty phases until maintenance is possible. The efficient utilization of increased number of phases is studied and the result under different operating condition is shown in fig 1. Also multiphase motor drives posses many other advantages over the traditional three-phase motor drives such as reducing the stator current per phase without increasing the voltage per phase, lowering the dc link current harmonics and higher reliability [1]-[3]. By increasing the number of phases it is also possible to increase the torque per rms ampere for the same volume machine [4], [5].

In this paper, a fractional slot interior permanent motor is designed to reduce the reluctance torque .The use of fractional slot winding not only reduces the amplitude of the cogging torque but also increases the fundamental order since the stator slots are located at different relative circumferential positions with respect to the edges of the magnets. In general the higher the LCM between the number of poles and number of slots the lower the cogging torque while the smaller the GCD between the number of poles and number of slots the lower the cogging torque. The use of interior permanent magnet reduces the inertia due to its reduced rotor diameter. Hence interior rotor motor is preferred in areas where lower rotor inertia is required.

This paper presents a five phase BLDC motor designed or high power density application. The

foundation of the motor design is a motor with fault tolerance, high reliability, compact structure and low weight .A five phase BLDC motor has been designed and simulation results are presented to validate the design.



Figure 1.Torque by different number of phases under different fault conditions for current amplitude of 1A.

## 2. DESIGN OF THE PROPOSED MOTOR

The motor is designed by using the design equations from [6],[7]. The EMF contributing to the electromagnetic power is:

$$E = (N_{ph} - 1)2\pi N_t k_w \alpha D_r L B_q n \tag{1}$$

where L is the active motor length,  $D_r$  is the rotor outer diameter,  $N_{ph}$  is the number of phases,  $N_{ph}$ -1 is the number of phases conducting simultaneously,  $N_t$  the number of turns per phase,  $k_w$  is the winding factor,  $\alpha$  is the pole arc coefficient,  $B_g$  the air-gap magnetic flux density and n the rotational speed in rev/s. The electromagnetic torque is:

$$T = \frac{P_o}{2\pi n} = \frac{EI_s}{2\pi n} = (N_{ph} - 1)N_t k_w a D_r L B_g I_s$$
(2)

where,  $I_s$  is the current amplitude[8,9].

The electromagnetic power  $(P_0)$  and torque are always positive because negative EMF times with negative current feeding gives a positive product.

The requirement of the proposed motor is given in Table 1.

Using equations (1) and (2), it is possible to calculate the number of turns. The design parameter mainly focuses on reduced cogging torque, and hence slot per pole combination is considered to obtain a reduced value of cogging torque. The features of the proposed motor design are summarized in Table 2.

Table 1. Motor specifications				
Parameter	value	unit		
Supply voltage	28	V		
Rotor outer diameter	90	mm		
Stator outer diameter	110	mm		
Rated Speed	440	rpm		
Required torque	3	Nm		
Stack length	24	mm		
Air gap flux density	0.8	Т		

Title of manuscript is short and clear, implies research results (First Author)

With the design objective of maximizing motor efficiency and torque, keeping the motor dimensions and ratings same as in the given parameters, first attempt was to select slot per pole combination. Various combination of slots and poles are studied and it is seen that 16 poles and 60 slots are a perfect combination for the application. The copper loss can be reduced with the increased number poles because end windings become shorter. But the increase in number of poles can lead to increased switching frequency and hence an increase in iron losses. Considering the application requirements (like, maximum speed, supply voltage, frequency, continuous power and torque requirement), design steps were done.

Table 2.Selection of Poles, Slots and Phases							
Change	Cogging torque	Speed	Torque	material utilized	cost		
poles	-			-	-		
increased	Reduced	Reduced	Increased	Increased	Increased		
teeth							
increased	Reduced	No	No	Increased	Increased		
		change	change				
phases							
increased	Reduced	No	No	Increased	Increased		
		change	change				

The air-gap flux density depends on the type of configuration and permanent magnet properties. The use of rare earth magnets may allow values higher than 1.0T. Samarium cobalt magnets are suitable for our application due to their high energy density 20MGOe residual flux density  $B_r$  at 20 °C is .9T, the coercive field strength Hc is 730 kA/m, and the max operating temperature 250°. From (2), the torque developed by the motor increases as the air gap flux density is increased. Thus we need to increase the air gap flux density for maximizing the motor efficiency and torque. Also a higher air gap flux density is advantageous so that the armature current is reduced to deliver the same torque level. So the effective air gap length is taken using Carter's coefficient, equation (3).

$$g' = gk_c$$

where  $k_c$ -Carter's coefficient

The proposed motor design details are given in Table 3.

Table 3.Motor design details					
Parameter	Value	unit			
Number of poles	16				
Number of slots	60				
Magnet	SmCo5				
Magnet thickness	4.5	mm			
Length of the magnet	12.3	mm			
Number of turns per phase	128				

# 3. FINITE ELEMENT MODELING AND RESULTS

By using the finite element analysis (FEA) it is possible to solve the electromagnetic state of the machine. When the machine geometry is described into the FEA-software, the value of the flux created by the permanent magnets, PM can be solved. This is an important value for the calculating of the induced back EMF. Fig.2 shows the main features of the five phase machine under study. The rotor carries surface mounted permanent magnets of alternate polarities making a succession of north and south poles.

The simulation shows how the circular motion of a rotor with permanent magnet generate an induced EMF in a stator winding. The generated voltage is evaluated as a function of time during the rotation. The centre of the rotor consists of silicon steel. The stator is made of the same material as the rotor

(3)

confining the field in closed loops through the winding. 2D-FEM model of the BLDC motor is built. The flux densities in the motor are shown in Figure 3 which verifies the motor design.



Figure 2. Five-phase PM BLDC motor: cross -sectional structure and winding distribution



Figure 3. The flux densities in the motor

Figure 4 shows the flux density in the air gap which is .8T as required. The ripple in the plot is due to the slot opening in the motor.



Figure 4. Flux density in motor air gap=0.8T

The 2D FEM analysis has also shown us that the phase voltage, voltage across adjacent and non adjacent phases of the multiphase winding motor differs as expected. This is shown in Figure 5.



Figure 5. Comparison of phase voltage, voltages in adjacent and non adjacent phases

The electromotive force (EMF) of stator winding is critical to the design and analysis of PM synchronous motor. No-load EMF, namely, E is induced by no-load air gap flux density. The value of emf is relative to stator current, motor efficiency and the amount of permanent magnets. The simulated back EMF is as in Figure 6, which shows the reduced ripple amplitude and incessed ripple frequency. The peak to peak

ripple percentage in the five phase topology is reduced to 4.5%. Cogging torque of the motor was calculated using finite element analysis and the plots are shown in Figure 7.





Figure 7. Cogging torque of the designed motor

## 4. CONCLUSION

This paper discussed the advantages of multiphase validating for torque for a current of 1A. Further the design details or the proposed motor is calculated from the design equations and knowledge. Finite element modeling of the proposed motor is done and the analysis results are shown. The experimental verification of these results, the motor will be fabricated and the tests will be conducted in the due course of time.

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